Seismic Performance Variation of Reinforced Concreate Columns with Increased Axial Load

2017 NZSEE Conference

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ABSTRACT: When reinforced concrete frames with brittle columns are affected by severe earthquakes, the failure of the brittle columns leads to the redistribution of axial load. Some of the axial load sustained by the failed columns is transferred to neighbouring columns through girders. Therefore, if the axial load to which the columns are subjected to increases to more than the initial value, the structural integrity of the columns can deteriorate to the extent that they are in danger of collapse. This study aims to investigate the effects of axial load increase on column collapse behaviour. Half-scale column specimens were fabricated and loaded horizontally until the loss of axial-load carrying capacity under increased axial load and constant axial load. The effects of lateral drift at the axial load increase on column collapse drift were investigated. The test results show that the columns for which the initial axial load increased during loading exhibited smaller collapse drift than columns for which the initial axial load was kept constant. These findings are useful in order to accurately evaluate the seismic performance variation of RC buildings with axial load redistribution.

1 INTRODUCTION

Many reinforced concrete (RC) buildings with brittle columns are in danger of collapse in the event of gravity load collapse of columns following shear failures from future earthquakes. In structural frames, once the brittle columns are severely damaged, some of the axial load sustained by them is transferred to neighbouring columns through girders (Fig. 1). In other words, the axial load of the first damaged columns decreases, while the axial load of the neighbouring columns increases to more than the initial value (Elwood and Moehle, 2003). In the past, for revealing such behaviour of RC columns, tests with decreased axial load were performed (Nakamura and Yoshimura, 2014). However, tests with increased axial load are yet to be conducted. As a result of the increase in the axial load, the structural integrity of the columns will deteriorate such that they are in danger of collapse. However, the process of such collapse is still unclear. This study aims to investigate the effects of axial load increase on column collapse behaviour. Half-scale column specimens were fabricated and loaded horizontally until the loss of axial-load carrying capacity under increased axial load and constant axial load. The effects of lateral drift at the axial load increase on column collapse drift are investigated. The findings are useful in order to accurately evaluate the seismic performance variation of RC buildings with axial load redistribution.

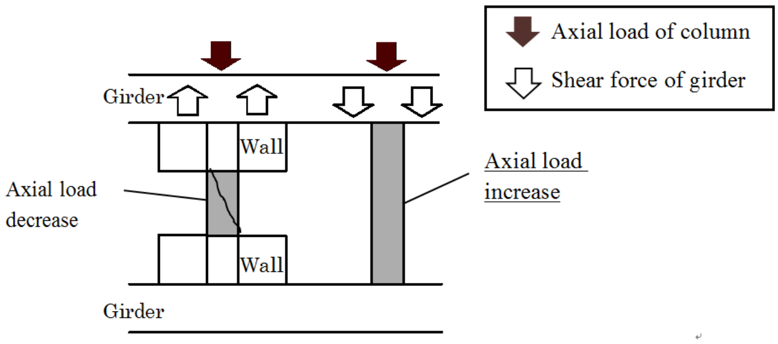


Figure 1. Mechanism of axial load increase

2 OUTLINE OF TEST

2.1 Specimen

Eight full-scale column specimens were fabricated and designed to ensure shear failure. Table 1 lists the structural properties of the specimens. The eight specimens have the same reinforcement specifications and loading history, but different loading methods for the axial load. Table 2 lists the material properties of the specimens. Normal reinforcement and concrete were used. The reinforcement details and the column sections of the specimens are shown in Figure 2. The column height was 1200 mm, the column section was 300 mm × 300 mm, and the height-to-depth ratio was 4.0. The longitudinal bar ratio (p_g), defined as the total main reinforcement area divided by the column section, was 2.65%. The transverse bar ratio (p_w) was 0.21%.

The specimens with increased and constant axial load were compared. The test variables were the drift at axial load increase and the axial stress ratio (η) after axial load increase. Note that the η is defined as the axial load multiplied by the concrete strength multiplied by the column section. For the specimens with increased axial load (see Table 1, from N2-30A to N2-30B09), the initial axial stress ratio (η) was 0.2. The η increased to 0.3 or 0.25 during loading. We assumed that the drift at axial load increase varies depending on the first damaged columns whose axial load decreases in the structural frame. Therefore, the five levels of drift at axial load increase (4.5%, 3.75%, 2.5%, 0.9%, and 0.75%) are examined. For the specimens with constant axial load (Takaine, et al., 2003), the η were 0.2 and 0.3 for specimens No.1 and No.4, respectively (see Table 1). Here, the η = 0.2 and 0.3 are the same as the initial and increased axial stress ratio of specimens with increased axial load, respectively.

Table 1 also lists the shear and flexure strengths computed for each specimen using the conventional method in Japan (Architectural Institute of Japan, 1991).

Table 1. Structural properties of the specimens

Name	Width×depth b×D (mm×mm)	Height h_0 (mm)	h_0/D	Longitudinal bar ratio p_g (%)	Transverse bar ratio p_w (%)	Axial stress ratio η	Drift at axial load increase (%)	Computed strength		
								Shear strength V_S (kN)	Flexure strength V_f (kN)	Shear / Flexure V_S / V_f
N2-30A	300 × 300	1200	4.0	2.65 [12-D16]	0.21 [2-D6@100]	0.2 → 0.3	3.75	180	278	0.65
N2-25A						0.2 → 0.25				
N2-30B						0.2 → 0.3	0.75			
N2-30A45						0.2 → 0.3	4.5	180	247	0.73
N2-30A25						0.2 → 0.3	2.5			
N2-30B09						0.2 → 0.3	0.9			
No.1						0.2 (Constant)	—	177	241	0.73
No.4						0.3 (Constant)	—	197	276	0.71

Table 2. Material properties of the specimens

(a) Steel

Specimen		Yield stress (N/mm^2)	Strain at yield stress (%)
N2-30A, N2-25A, N2-30B	D16	378	0.20
	D6	400	0.27
N2-30A45, N2-30A25, N2-30B09	D16	351	0.24
	D6	385	0.23
No.1, No.4	D16	402	0.24
	D6	392	0.24

(b) Concrete

Specimen	Max. stress σ_B (N/mm^2)	Strain at Max. stress (%)
N2-30A, N2-25A, N2-30B	29.9	0.19
N2-30A45, N2-30A25, N2-30B09	29.7	0.22
No.1, No.4	30.7	0.22

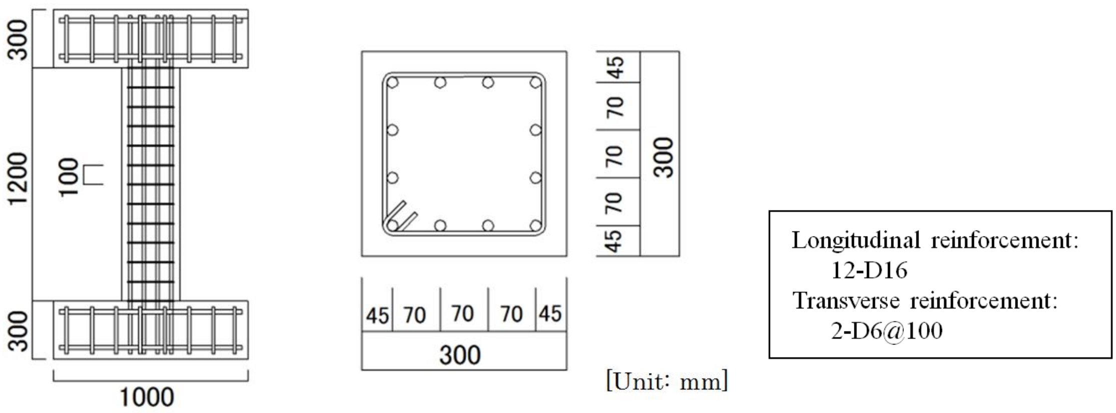


Figure 2. Reinforcement details and column section

2.2 **Loading method**

Figure 3 illustrates the test apparatus that realizes double-curvature deformation. The specimens were laterally loaded under increased or constant axial load. The tests were terminated when the specimens could not sustain the prescribed axial load.

With respect to the loading history, we used cyclic loadings. Figure 4 shows the detailed loading history: the lateral drifts were divided by the column height. The specimens were finally loaded to the positive direction for as long as the axial load could be maintained.

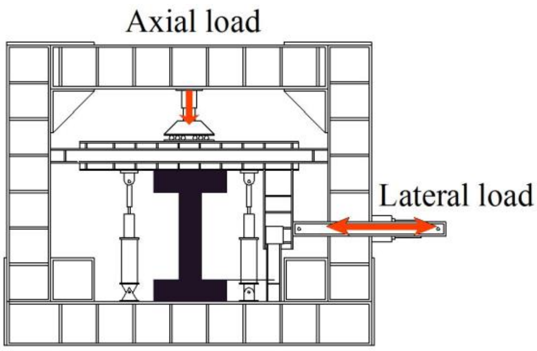


Figure 3. Test apparatus

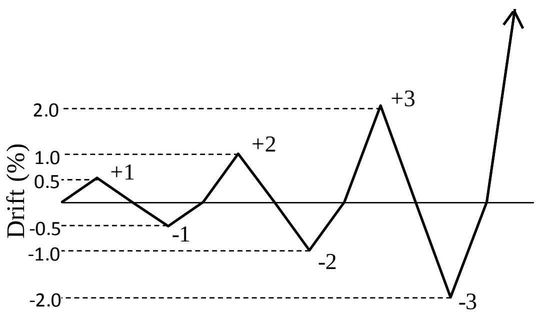


Figure 4. Loading history

3 **TEST RESULTS**

3.1 **Collapse procedure**

All specimens failed in shear, and finally lost their axial load-carrying capacity except specimens N2-30A45 and N2-30A25. In this study, “collapse” and “collapse drift” are defined as the column’s loss of axial load-carrying capacity and the maximum lateral drift experienced prior to collapse, respectively. The test results are presented in Table 3. The drifts and axial deformations were divided by the column height. Note that the tests for N2-30A45 and N2-30A25 were terminated before the specimens lost the axial load-carrying capacity owing to the limit of allowable lateral drift determined by the specifications of the test apparatus. However, we regarded the lateral drift at the final step as the collapse drift for N2-30A45 and N2-30A25 because the columns were assumed to be on the edge of collapsing owing to large damages.

Table 3. Test results

Specimen	Maximum load (kN)	Drift at max. load (%)	Drift at axial load increase (%)	Collapse drift (%)	Axial deformation at collapse (%)
N2-30A	220	0.99	3.75	4.62	0.34
N2-25A	234	1.00	3.75	6.88	1.07
N2-30B	237	0.95	0.75	2.0	0.52
N2-30A45	222	1.00	4.50	5.75	0.38
N2-30A25	220	1.00	2.50	5.58	0.30
N2-30B09	226	1.00	0.90	2.18	0.05
No.1	231	0.97	—	13.4	1.96
No.4	253	1.01	—	2.0	0.48

The collapse behavior is presented below in order to compare specimens N2-30A, N2-25A, and No.1, as well as compare specimens N2-30B and No.4.

N2-30A, N2-25A, and No.1

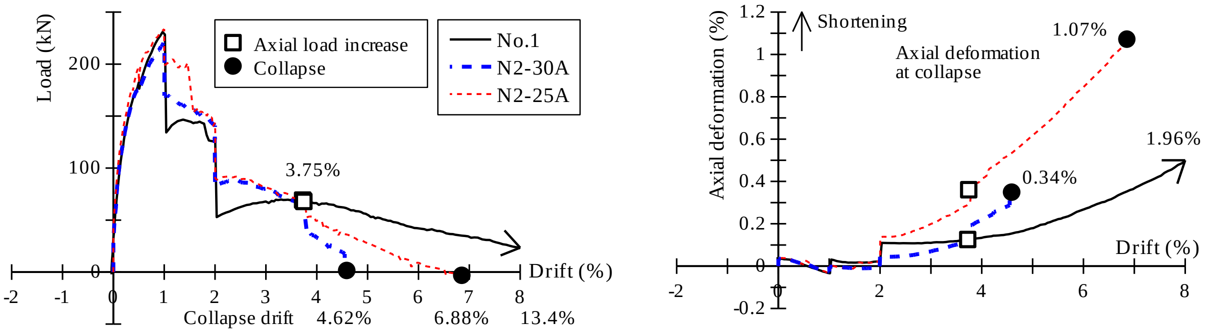
Figure 5(a) shows the lateral load and the lateral drift relations for specimens No.1, N2-30A, and N2-25A, while Figure 5(b) shows the lateral drift and the axial deformation relations for specimens No.1, N2-30A, and N2-25A. Figures 5(a) and 5(b) are the skeleton curves of the positive direction where the collapse occurred. For N2-30A and N2-25A, the axial loads were increased after maximum load in the load-degrading regions. In Figures 5(a) and 5(b), the square indicates the point where the axial load was increased, while each circle indicates the collapse. The constant axial load of specimen No.1 was the same as the initial axial loads of specimens N2-30A and N2-25A. Figure 7 shows the damage stages of specimen N2-30A observed at the maximum load, the shear failure, and after collapse. As shown in Figure 5(a), the specimens collapsed when the lateral load decreased to approximately zero. At the moment of collapse, fractures at the transverse bar and loosening at the hook, as well as buckling of the longitudinal reinforcements were observed. A similar behaviour was observed at the collapse of the other specimens.

As shown in Figure 5(a), the strength reduction of specimen N2-30A after the axial load increase was greater than that of specimen No.1 with constant axial load. The collapse drift of specimen N2-30A was 4.62% and that of specimen No.1 was 13.4%. The former was 0.34 times smaller than the latter. Figure 8 shows the collapse drifts and the decreasing rates of collapse drifts of specimens No.1, N2-30A, and N2-25A. The collapse drift was smaller in columns with increased axial load than in columns with constant axial load. A similar pattern was observed in other specimens. As shown in Figures 5(a), the larger the axial load increase in specimens N2-30A and N2-25A, the larger the reduction in strength. Furthermore, the collapse drift of N2-30A (4.62%) was smaller than that of N2-25A (6.88%). Therefore, the collapse drift decreases as the axial load after axial load increase increases. In summary, columns with increased initial axial load exhibited smaller collapse drifts than columns with constant initial axial load; furthermore, the collapse drift decreases as the axial load after axial load increase increases, even when the columns have the same drift at axial load increase.

As shown in Figure 5(b), the axial deformation increase rates of specimens N2-30A and N2-25A after the axial load increase were greater than that of specimen No.1 with constant axial load. The axial deformation at collapse for N2-30A, N2-25A, and No.1 were 0.34%, 1.07% and 1.96%, respectively. Therefore, columns for which the initial axial load increased after maximum load exhibited smaller axial deformation at collapse than columns for which the initial axial load was kept constant, and the axial deformation decreases as the axial load after axial load increase increases.

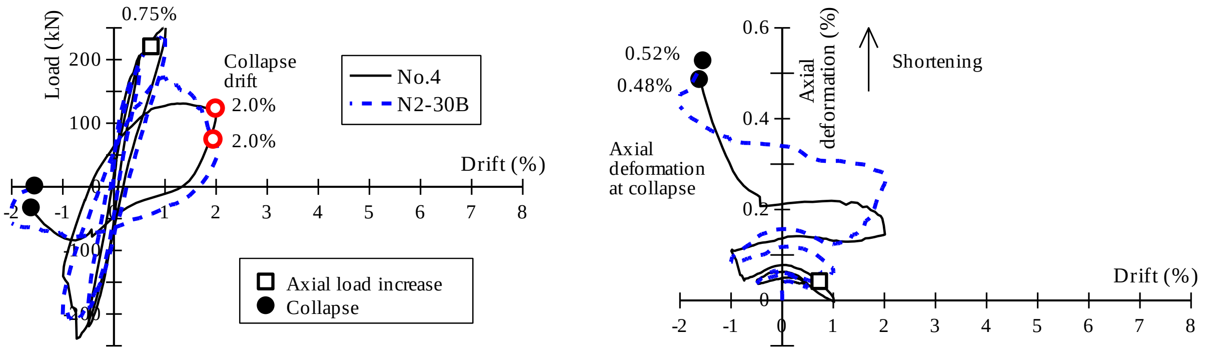
N2-30B and No.4

Figure 6(a) shows the lateral load and lateral drift relations of specimens No.4 and N2-30B while Figure 6(b) shows the lateral drift and axial deformation relations of specimens N2-30B and No.4. For specimen N2-30B, the axial load was increased before the maximum load when the drift was small. The constant axial load of specimen No.4 was the same as the final axial load (increased value) of specimen N2-30B. Both specimens collapsed during cyclic loading. According to the definition of collapse drift, the collapse drifts of specimens No.4 and N2-30B were 2.0% (see Fig. 6(a)). Figure 6(b) indicates that the axial deformation of specimen N2-30B increased rapidly after axial load increase and approached that of specimen No.4. As a result, the axial deformations at collapse are nearly the same for specimens N2-30B and No.4 (approximately 0.5%). Therefore, columns for which the initial axial load increased before maximum load had the same collapse drift and axial deformation at collapse with columns for which the increased axial load was kept constant.



(a) Load vs. drift (b) Drift vs. axial deformation

Figure 5. Test results of No.1, N2-30A, and N2-25A



(a) Load vs. drift (b) Drift vs. axial deformation

Figure 6. Test results of No.4 and N2-30B

(a) At max. load (Drift = 0.99%) (b) At shear failure (-0.83%) (c) At collapse (4.62%)

Figure 7. Damage stages of N2-30A

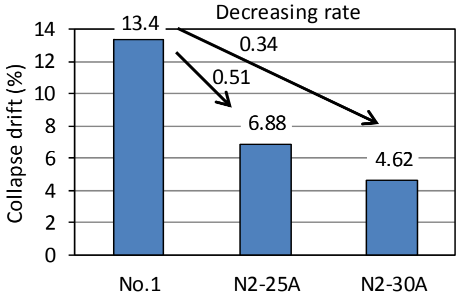


Figure 8. Comparison of collapse drifts of No.1, N2-30A, and N2-25A

3.2 Strain of longitudinal reinforcement

In this section, axial load increase behaviour is discussed based on the strain measurements of longitudinal reinforcement. Figure 9 shows the strain gauge locations of longitudinal reinforcement for specimens No.1, N2-30A, and N2-25A. Figure 10 shows the longitudinal reinforcement strains of strain gauge L16 for these three specimens. The figure indicates that the strain of specimen No.1 was lower than the yield strain of the longitudinal reinforcement before the drift of 7%. In contrast, the strains of specimens N2-30A and N2-25A increased rapidly after axial load increase and exceeded the yield level in compression. Further, the strains increased rapidly as the axial load after axial load increase increased (N2-30A > N2-25A). As a result, the collapse drift and the axial deformation at collapse of N2-30A were smaller than those of N2-25A (see Fig.5). Note that the gauge location was close to the shear crack (Fig. 7(c)), indicating that concrete crushing near the failure line led to the increase in compression strain in longitudinal reinforcements for these locations with axial load increase. It is likely that the main reinforcements played an important role in sustaining axial load at large drift levels.

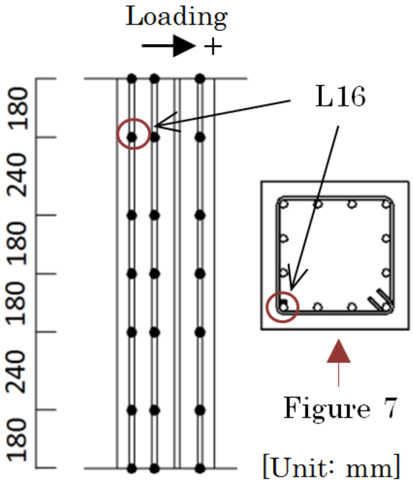


Figure 9. Strain gauge location of No.1, N2-30A, and N2-25A

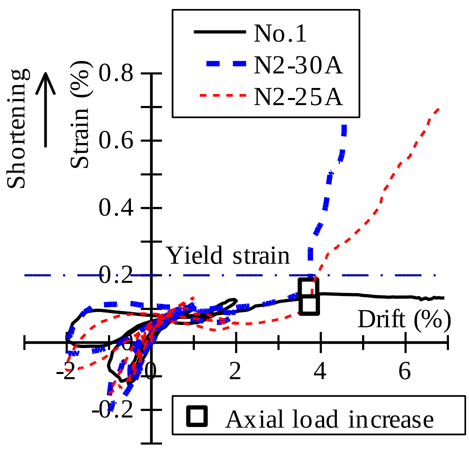


Figure 10. Drift vs. longitudinal bar strain of No.1, N2-30A, and N2-25A

3.3 Effects of axial stress ratio

Figure 11 shows the axial stress ratio (η) versus collapse drift relations for all specimens. Figure 12 shows the axial stress ratio (η) versus axial deformation at collapse relations for all specimens. For specimens with increased axial load, the axial stress ratio was plotted using both the initial and increased axial load. Figures 11 and 12 indicate that the collapse drifts and axial deformations at collapse vary widely for the same η (initial value). In contrast, there are correlations between the collapse drift and η (increased value), and between the axial deformation at collapse and η (increased value). These results indicate that the near-collapse axial load (increased axial load) significantly affects the collapse behaviour. However, in Figures 11 and 12, collapse drifts and axial deformations at collapse vary slightly for the same η (increased value: η = 0.3). We took into consideration the effects of the difference in the drift at axial load increase. Further studies are necessary to investigate the effects of the axial load increasing point on the collapse behaviour.

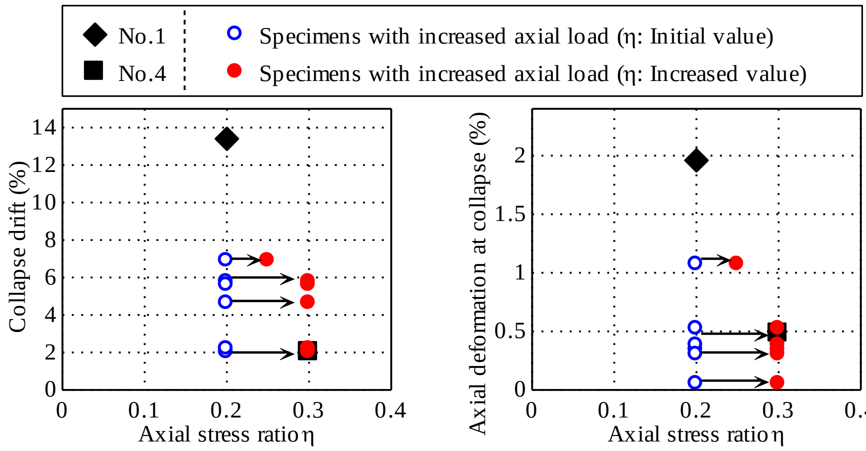


Figure 11. Axial stress ratio vs. collapse drift

Figure 12. Axial stress ratio vs. axial deformation at collapse

3.4 **Effects of drift at axial load increase**

Figure 13 shows the drift at axial load increase versus collapse drift relations for specimens with axial stress ratios after axial load increase of 0.3. The figure also shows the collapse drifts of specimens with constant axial load. The collapse drifts of specimens with increased axial load ranged from the value for specimen No.4 (increased axial load kept constant) to the value for specimen No.1 (initial axial load kept constant). Further, the smaller the drift at axial load increase, the smaller the collapse drift. The fitted line plot approximated by the least square method and its equation are shown in the Figure 13.

Figure 14 shows the drift at axial load increase versus axial deformation at collapse relations for specimens with axial stress ratios after axial load increase of 0.3. The figure also shows the axial deformation at collapse of specimens with constant axial load. The axial deformations at collapse of specimens with increased axial load were smaller than that of specimen No.1 for which the initial axial load was kept constant. Further, the smaller the drift at axial load increase, the smaller the axial deformation at collapse, except for specimen N2-30B. Note that the axial deformations at collapse of specimens N2-30B and No.4 were rather large because they only collapsed during cyclic loading (see Fig. 6(b)).

In summary, the drift at axial load increase significantly influences the collapse drift and the axial deformation at collapse, and the sooner the axial load increases, the sooner the column collapses.

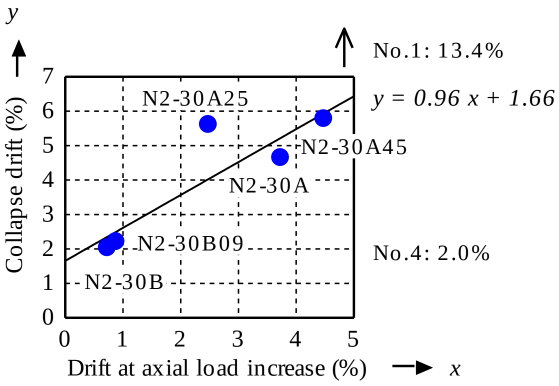


Figure 13. Drift at axial load increase vs. collapse drift

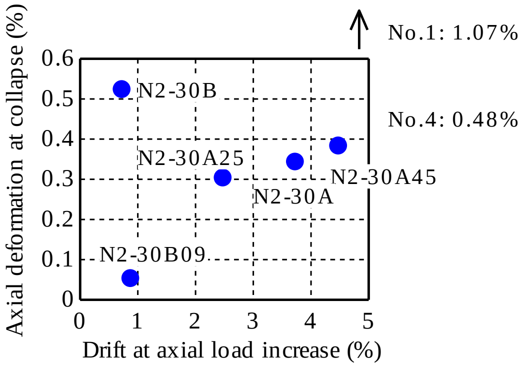


Figure 14. Drift at axial load increase vs. axial deformation at collapse

4 CONCLUSIONS

The effects of increased axial load on the collapse behaviour of shear failing RC columns due to axial load redistribution in structural frames were investigated. The major findings of this study are summarized below.

1) Columns for which the initial axial load increased exhibited smaller collapse drift than columns for which the initial axial load was kept constant.

2) Columns for which the initial axial load increased before maximum load exhibited the same level of collapse drift with columns for which the axial load increase were kept constant from the beginning.

3) The collapse drift and axial deformation at collapse decreased as the axial load after the axial load increase increases, even when the columns have the same drift at axial load increase. The near-collapse axial load (increased axial load) significantly affects the collapse behaviour.

4) The drift at axial load increase influences collapse behaviour. The smaller the drift at axial load increase, the smaller the collapse drift and axial deformation at collapse. Therefore, the sooner the axial load increases, the sooner the column collapses.

ACKNOWLEDGEMENT

This study was supported by the Japan Society for the Promotion of Science Grants-in-Aid for Scientific Research Grant: Number 25420573.

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